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BUREAU OF ENGINEERING RESEARCH

STUDY OF ATMOSPHERIC EFFECTS ON LASER COMMUNICATIONS SYSTEMS

by

William E. Webb, Project Director

Interim Report on Contract NAS8-25562

March 1971

BER

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National Aeronautics and Space Administration
Huntsville, Alabama 35812

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Bureau of Engineering Research
University of Alabama
University, Alabama 35486

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SUMMARY REPORT

The research conducted during the past year under NASA Contract NAS8-25562 has consisted of two separate and relatively independent investigations. The first part of the contract period was devoted to the completion of a study of the effects of atmospheric turbulence on the propagation of a 10.6 micron laser beam. This work, which was begun under a previous NASA Contract (NAS8-30507), was completed in June, 1970.[1] Since that time we have directed our primary efforts toward the investigation of a number of problems relating to the Marshall Space Flight Center's High Altitude Aircraft Test Project for Visible Optical Laser Communications.

Because of the independent nature of the two aspects of the research, we have divided this report into two parts each dealing with a separate phase of the project. Volume One contains reports on the various analyses which have been made in connection with the MSFC High Altitude Aircraft Test. These analyses include an investigation of the effects of the aircraft navigational errors on experimental accuracy, a survey of the engineering measurements to be conducted on this experiment and a survey of the meterological support requirements for the project. In addition a brief description of the High Altitude Aircraft Test program is given as background for the reader who may not be familiar with this project. Volume Two contains a complete report of both the experimental and theoretical investigations of the propagation of a 10.6 micron laser beam through the turbulent atmosphere and an analysis of the effects of atmospheric turbulence on the operation of a CO_2 laser heterodyne communications system. It has been our intention that each volume of this report should be as nearly self-contained as possible. Each section therefore contains separate tables of contents and references.

In addition to the results reported herein a small amount of project time has been devoted to the development of a high energy pulsed laser to be used for the study of atmospheric effects on pulsed laser systems and to the planning of experiments in this area. A proposal for the continuation of this work as well as for the continuation of our analysis in support of the MSFC optical communications experiments has been submitted.

DESCRIPTION OF THE MSFC HIGH ALTITUDE AIRCRAFT TEST FOR VISIBLE LASER COMMUNICATIONS

Introduction

The analysis reported in the following sections have been performed in support of the High Altitude Aircraft Test of Visible Laser Communications being conducted by MSFC personnel during 1971-1972. In order to orient the reader as to the relation of this work to the overall MSFC Aircraft Test program a brief description of that experiment will be given. A more comprehensive discussion of the experiment can be found in the High Altitude Aircraft Test project plan [2].

Program Objectives

The High Altitude Aircraft Test for Visible Laser Optical Communications (hereafter referred to as HAAT) is intended to perform three functions, viz., to collect scientific data on the propagation of visible wavelength radiation through the atmosphere, to provide engineering data needed for the evaluation of the techniques of optical communications and for the design of future systems, and to demonstrate the feasibility of optical techniques for communications between aircraft and ground or satellite and ground. These techniques include the ability of the satellite (or aircraft) to acquire the ground station and vice versa, the ability to accurately track the moving satellite and the ability to transmit high data rates with low error and high reliability.

Experimental System

The experimental system consists of an airborne optical communications terminal carried aboard a modified RB-57 aircraft and a ground station located on Redstone Arsenal, Alabama. Both the airborne and ground terminals are equipped with transmitting lasers so that two way communications may be established and both uplink and downlink propagation may be studied. In addition to communication equipment each terminal contains an optical tracking system which controls its pointing during the experiment. Thus each end of the system cooperatively tracks upon the other end throughout the course of the experiment. The ground station is equipped with a separate laser radar (designated the Ground Based Acquisition Aid or GBAA) for initial acquisition of the aircraft and for providing exact range and zenith angle information throughout the experiment. Both the airborne and ground terminals are fully instrumented to record all pertinent data relating both to system operation and to atmospheric effects on optical propagation.

The downlink channel will consist of a 6328 Å He-Ne laser beam pulse code modulated at 30 M.bits/sec. Downlink transmission will consist of either a real time television picture, a pseudo random code word for bit error rate measurements, or telemetry of data being collected aboard the aircraft. The uplink channel will consist of an amplitude modulated 4880 Å Argon laser beam which will be used for uplink scintillation measurement and to transmit commands to the airborne package.

The ground terminal receiving and transmitting optics consists of a 24-inch Cassegrainian telescope with the experimental package located at its Coudé focus. The incoming 6328 Å beam from the airborne He-Ne laser passes through a wavelength selective beam splitter to separate it from the 4880 Å uplink beam. It is then directed by means of a second beam splitter to two detectors. The first detector is a quadrant photomultiplier which provides fine pointing signals. These signals, along with the output of the angle encoders on the telescope mount, are fed into a SCC 4700 computer which performs the necessary coordinates transformations and generates the signals to drive the polar-equitorial telescope mount. In addition, both the angle encoder and the quadrant photomultiplier outputs are recorded to give angle of arrival fluctuation data.

The second part of the incoming beam is directed to two photomultiplier tubes. The output of one of these detectors is recorded to provide the wide bandwidth downlink communication, channel output, scintillation data, and bit error rate data.

The uplink beam is generated by an Argon laser which passes through a modulator and a beam steerer and out through the telescope. The beam steerer is driven by the computer so as to direct the uplink beam directly back along the incoming beam. The uplink beam is modulated with a 10.7 MHz sine wave and also with audio tones used to control the operation of the aircraft terminal.

In addition to the main tracking and communications system, the ground terminal contains a laser radar for acquisition and ranging (the GBAA). The acquisition radar is mounted on the main telescope tube and bore-sighted with it. It consists of pulsed Argon laser, beam steering optics and receiving electronics. During acquisition phase, the beam is digitally scanned in a raster pattern, until a return from corner reflectors mounted on the aircraft is detected. At this time the GBAA enters a limited scan mode and the tracking and pointing function is passed to the detector in the primary receiver system. The GBAA continues to track the aircraft, however, and to provide range information. In the event that the primary tracker should lose the target, the acquisition radar will automatically re-enter the acquisition mode and reacquire the target. During this time the telescope drive will enter a coast mode so as to continue to point at the assumed position of the aircraft.

The airborne optical system will be mounted in a fixed position aboard the RB-57 aircraft and will view the ground in a steerable mirror which will be servocontrolled to point the outgoing beam in the proper direction. During acquisition the steerable mirror is pointed in the general direction of the ground station manually. When the ground based acquisition radar illuminates the aircraft, an acquisition sensor detects the upcoming beam and causes the system to enter a track mode. The incoming beam passes through a dichroic beam splitter which isolates it from the outgoing beam to an image dissector which provides tracking information and a photomultiplier which detects upcoming commands and measures scintillation. The transmitter section of the airborne terminal consists of a He-Ne laser which is superimposed on the incoming beam by means of the dichroic beam splitter. The outgoing beam is pulse code modulated at 30 megabits/sec with either a pseudo random word for bit error rate measurements, with a video signal generated by a television camera aimed at the ground, or with telemetry.

Experiment Plan

The experiment plan calls for four missions at various times during the year. Each mission will consist of four fly overs of about three hours duration.

The aircraft will approach the Madkin Mountain ground station on a straight line path at an altitude of about 50,000 feet. Once acquired by the GBAA radar the aircraft will assume a circular flight path centered on the ground terminal thus maintaining a constant range from the ground station and constant zenith angle. Initially an altitude of 70,000 feet and a path diameter of 10 miles is planned. This corresponds to a start range of 74,800 feet and a zenith angle of 20.6 degrees, the minimum zenith angle obtainable with a circular path. By varying the altitude of the aircraft and the diameter of it's flight path the range and zenith angle can be varied at will.

The scientific measurements to be made during each fly-over are outlined in Table I. Detailed discussions of these experiments can be found in the referenced measurement program document [2].

Table I. Measurements Outline

Quantity Measured	Parameters	Analysis to Yield
1. Scintillation (downlink)	Receiving Aperture Range Zenith Angle	Log amplitude variance Probability density function Verify theoretical predictions concerning zenith angle, and range dependence. Aperture averaging effects: a. Reduction of signal variance b. Change of probability density function. Difference in up and down link.
2. Scintillation (uplink)	Receiving Aperture Range Transmitter Aperture	Log amplitude variance Probability density function Verify theoretical prediction concerning zenith angle and range dependence. Verify no uplink aperture averaging Effect of transmitting aperture size. Differences in uplink and downlink.
3. Angle of Arrival Fluctuations (downlink)	Range Zenith Angle Receiving Aperture	Variance Probability density function Aperture averaging Dependence on range and zenith angle. Differences between uplink and downlink.
4. Angle of Arrival Fluctuations (uplink)	Range Zenith Angle	Variance Probability density function Dependence on range and zenith angle. Differences between uplink and downlink.
5. Bit Error Rate	Range Zenith Angle Beam Divergence Transmitter Power	Verify theoretical prediction of BER dependence on system noise and irradiance fluctuation variance.

Table I. Measurements Outline (Cont'd)

Quantity Measured	Parameters	Analysis to Yield
6. Atmospheric Transmittance	None	Atmospheric transmittance at optical wavelengths.
7. Engineering Measurements		Determine ability to acquire and track. Evaluate system performance.

ANALYSIS OF THE ERRORS IN THE MSFC OPTICAL COMMUNICATIONS EXPERIMENT DUE TO FLIGHT PATH INACCURACIES

Introduction

Marshall Space Flight Center's High Altitude Aircraft Test of Visible Laser Communications (HAAT) is expected to provide scientific data concerning atmospheric turbulence and its effect on the propagation of laser beams over near vertical paths. If these data are to be meaningful, it is necessary that certain parameters such as aircraft range and zenith angle be held constant. Clearly no aircraft can fly a precise path, so some variation in these parameters must be accepted. It is the purpose of this report to examine the errors introduced into the experimental data as the result of deviation of the aircraft from its prescribed flight path and, based on this analysis, to suggest the maximum deviations which can be tolerated.

General Considerations

A description of the HAAT experiment is found in the HAAT project plan [2]. During the test the aircraft will fly a circular pattern over the ground station, ideally maintaining a constant range and zenith angle. The ground station will track the aircraft by means of a ground based acquisition aid (GBAA) also used for initial contact. The GBAA is an optical laser radar with ranging facilities and will provide continuous range and angle information. From the GBAA data the aircraft's position relative to the ground station will be accurately known, a posteriori. It is therefore not a requirement that the aircraft fly precisely along a predetermined path but only that it remain upon a circle reasonably close to the desired pattern. It is the variations of the aircraft path from this somewhat arbitrary circle which are important. The GBAA data will also allow the elimination of any data segment for which the variation in the range or zenith angle are excessive.

If the aircraft were to fly a perfectly level, circular path then its range (r) and zenith angle (θ) would be constant. We anticipate that the aircraft's actual path will be some smooth curve which approximates the prescribed circular pattern. We will therefore assume that θ and r will be slowly varying functions of time.

The quantities to be measured (such as scintillation) are statistical quantities whose mean and variance depend upon r and θ as well as upon the statistics of the atmospheric turbulence. Since the atmosphere itself is a non-stationary system, the time variation of r and θ will simply serve to increase the variation in the statistical parameter of the measured quantity. It therefore seems reasonable to require that the variation in the statistical estimates of these parameters due to aircraft motion be small compared to the variations introduced by such unavoidable effects as atmospheric non-stationarity.

Table I in Appendix B of the HAAT program plan [3], which has been reproduced as Table I of this report, describes seven measurements which will be made. Eliminating from consideration the Engineering measurements and neglecting any difference in uplink and downlink measurements, these may be reduced to four basic types of measurement viz.

1. Scintillation
2. Angle of Arrival Fluctuations
3. Bit Error Rate Measurements
4. Transmittance.

Each of these measurements will be considered.

Scintillation

The variance of the log-amplitude σ_ℓ for a spherical wave is given by [4]

$$\sigma_\ell = \int_0^Z C_N^2(h) \; [\frac{(z-s)s}{z}]^{5/6} \; ds \qquad (1)$$

where $C_N^2(h)$ is the index of refraction structure constant at an altitude h, z is the slant range and ds is an element of length along the propagation path. The actual situation which we wish to consider is that of a collimated, truncated gaussian beam. Since, however, we are only concerned with the order of magnitude of the variation of σ_ℓ on range and zenith angle, and since the form of the function $C_N^2(h)$ is not well known, we will assume that the relation of equation (1) describes the gaussian beam accurately enough for our purposes.

We will assume a form for $C_N^2(h)$ viz.

$$C_N^2(h) = C_0{}^2 \; h^{-1/3} \; e^{-h/h_0} \qquad (2)$$

where h_0 is a scale height usually taken to be 3200 m. Recent work [5] indicates that this value may be too large, however since for larger h_0, σ_ℓ is more sensitive to changes in altitude and zenith angle we will assume this value as a worst case.

For a zenith angle θ, h is related to s by

$$h = s \cos \theta \tag{3}$$

then

$$\sigma_{\ell}^{2} = C_{0}^{2} \cos^{-1/3} \theta \int_{0}^{z} s^{-1/3} e^{-\left(\frac{s \cos \theta}{h_0}\right)} \left[\frac{(z-s)s}{z} \right]^{5/6} ds \tag{4}$$

Now we let $u = s/z$, then

$$\sigma_{\ell}^{2} = C_{0}^{2} \cos^{-1/3} \theta \, z^{3/2} \int_{0}^{1} u^{1/2} (1-u)^{5/6} e^{-u\, z \cos \theta / h_o} du \tag{5}$$

But $z \cos \theta$ is just the aircraft altitude h_m, therefore

$$\sigma_{\ell}^{2} = C_{0}^{2} \cos^{-11/6} h_{m}^{3/2} \int_{0}^{1} u^{1/2} (1-u)^{5/6} e^{-\frac{h_m}{h_0} u} du \tag{6}$$

Now consider an aircraft flying in a circular path of radius R at an altitude h_m. As can be seen in Figure 1, if the radius of the circle changes by an amount ΔR then h_m remains constant and θ changes by an amount $\Delta\theta$ given by

$$\Delta\theta = \frac{\Delta X}{s} = \frac{\Delta R \cos \theta}{s} = \frac{h_m \Delta R}{s^2} \tag{7}$$

then the fractional change in the log amplitude variance is

$$\frac{\Delta\sigma_\ell^2}{\sigma_\ell^2} = \frac{1}{\sigma^2} \frac{\partial\sigma_\ell^2}{\partial\theta} \Delta\theta$$

$$= [+ \frac{11}{6} C_0^2 \cos^{-17/6} \theta \sin \theta\, h_m^{3/2}\, I(h_m)] \cdot \Delta\theta$$

$$\Big/ [C_0^2 \cos^{-11/6} \theta\, h_m^{3/2}\, I(h_m)] \qquad (8)$$

Where $I(h_m)$ denotes the definite integral in Equation 6. Equation 8 reduces to

$$E_{\Delta R} = \frac{\Delta\sigma_\ell^2}{\sigma_\ell^2} = \frac{11}{6} \tan \theta\Delta\theta \qquad (9)$$

or

$$E_{\Delta R} = \frac{11}{6} \frac{R\Delta R}{s^2} \qquad (10)$$

Equation 10 allows us to estimate the variation in σ_ℓ^2 for a change in horizontal position of the aircraft. A similar equation may be derived for a change in altitude ΔH. As can be seen from Figure 2, a change in aircraft altitude changes both h_m and θ. The change in θ is given by

$$\Delta\theta = \frac{\Delta X}{s} = - \frac{\Delta H_m \sin \theta}{s} = - \frac{R\ \Delta H_m}{s^2} \qquad (11)$$

then

$$\frac{\Delta\sigma_\ell^2}{\sigma_\ell^2} = \frac{1}{\sigma_\ell^2} \left[\frac{\partial\sigma_\ell^2}{\partial\theta} \Delta\theta + \frac{\partial\sigma_\ell^2}{\partial h_m} \Delta h_m \right] \qquad (12)$$

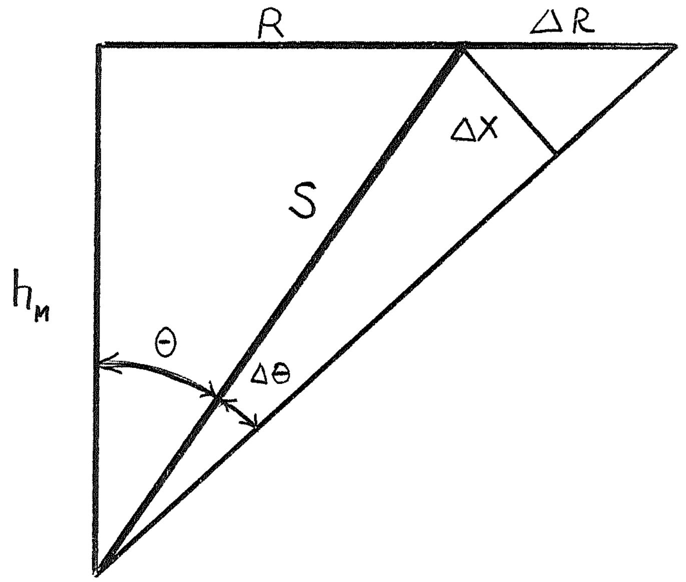

Figure 1

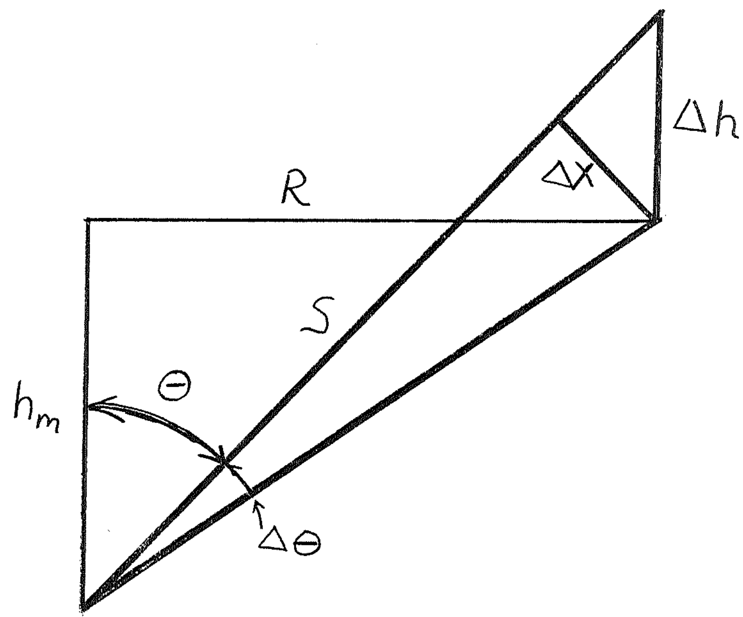

Figure 2

$$\frac{\Delta\sigma_\ell}{\sigma_\ell^2} = \frac{11}{6} \tan\theta\ \Delta\theta + \frac{3}{2} h_m^{-1}\ \Delta h_m + I^{-1}(h_m)\ \frac{\partial I(h_m)}{\partial h_m}\ \Delta h_m \qquad (13)$$

$$E_H = \frac{\Delta\sigma_\ell}{\sigma_\ell} = -\frac{11}{6}\ \frac{R^2}{S^2}\ \frac{\Delta H_m}{H_m} + \frac{3}{2}\ \frac{\Delta H_m}{H_m} + \frac{1}{I_m}\ \frac{\partial I_m(h_m)}{\partial h_m}\ \Delta H_m \qquad (14)$$

The last term in Equation 14 has been evaluated numerically on the IBM 360/50 computer using a double precision Simpson's rule integration. The values of this term are

- 2.45% per 1000 ft. at 42,000 feet
- 2.15% per 1000 ft. at 52,500 feet
- 1.90% per 1000 ft. at 63,000 feet.

Equation 10 and 14 specify the approximate errors in σ_ℓ^2 due to variation in ΔR and ΔH. These have been evaluated for the altitudes indicated above and for horizontal distances of 5 and 10 miles. The results are shown in Table II. The values for ΔE_H are seen to be quite small and may have either sign. This behavior may be understood by considering that for a positive ΔH, corresponding to an upward motion of the aircraft, the log amplitude variance is increased due to an increase in the propagation path length.

Table II

Altitude (1000's ft)	Range (Miles)	Slant Range (1000's ft.)	ΔE_R %/1000 ft.	ΔE_H %/1000 ft.	$\lvert\Delta E\rvert + \lvert\Delta H\rvert$ %/1000 ft.
42.0	5	49.2	2.0%	-.11%	2.1%
52.5	5	58.8	1.4%	+.005%	1.4%
63.0	5	68.3	1.04%	+.05%	1.1%
42.0	10	67.2	2.15%	.85%	3.0%
52.5	10	74.5	1.75%	1.11%	2.9%
63.0	10	82.1	1.44%	1.17%	2.6%

This effect is relatively slight; however, since C_N^2 at the altitudes we are considering is very small. Furthermore, it is compensated for by the decrease in zenith angle which tends to "swing" the propagation path up out of the more turbulent lower atmosphere. The variation in the horizontal distance has a larger effect since a positive ΔR (the aircraft moves outward from the ground station) both lengthens the propagation path and lowers it into a more turbulent region.

Angle of Arrival Fluctuations

The variance of the apparent angle of arrival can be shown to depend on the five-thirds power of the correlation length r_o [6.7], i.e.,

$$\langle \Delta\theta^2 \rangle \propto 1/r_o^{5/3} \tag{15}$$

For a spherical wave propagating from the ground to an aircraft at a slant range z. r_o may be expressed as

$$1/r_o^{5/2} \propto \int_0^Z C_N^2(h) \left(\frac{s}{z}\right)^{5/3} ds \tag{16}$$

or

$$1/r_o^{5/3} \propto \int_0^{z \cos\theta/h_o} (h_o u)^{-1/3} e^{-u} \left(\frac{u\, h_o}{z \cos\theta}\right)^{5/3} \left(\frac{h_o du}{\cos\theta}\right) \tag{17}$$

where we have let $u = s \cos\theta/h_o$. We note that $z \cos\theta$ is the aircraft altitude h_m, therefore

$$\langle \Delta\theta^2 \rangle \propto \frac{h_o^{7/3}}{h_m^{5/3} \cos\theta} \int_0^{h_m/h_o} e^{-u} u^{4/3} du \tag{18}$$

The integral in Equation 18 is the incomplete gamma function $\Gamma(h/h_o, 7/3)$ which, at the altitudes that we are considering, is a slowly varying function of h_m. We will therefore take it to be a constant and write

$$\langle \Delta\theta^2 \rangle \propto h_m^{-5/3} \cos^{-1} \theta \tag{19}$$

For changes in horizontal range

$$E_{\Delta R} = \frac{\Delta \langle \Delta\theta^2 \rangle}{\langle \Delta\theta^2 \rangle} = \mathrm{Tan}\ \theta\ \Delta\theta \tag{20}$$

or

$$E_{\Delta R} = \frac{R\Delta R}{s^2} \tag{21}$$

By comparing this expression with Equation 10, we see that the angle of arrival measurement errors are smaller than the scintillation measurement errors by a factor of 6/11 for changes in R. Hence the requirement on the accuracy of R is not determined by the angle of arrival measurements.

For changes in the aircraft altitude we may replace cos θ by h_m/s hence

$$\langle \Delta\theta^2 \rangle \propto h_m^{-7/3}\ s = h_m^{-7/8} \sqrt{R^2 + h_m^2} \tag{22}$$

then

$$E_{\Delta H} = (-\frac{7}{3} H_m^{-1} + H_m\ s^{-2}) \Delta H_m \tag{23}$$

For a five-mile radius E_H varies from 3.8% at 42,000 feet to 2.5% at 63,000 feet.

For downlink angle of arrival, the integral in Equation 16 is replaced by

$$\int_0^Z C_N^2(h)\ \left(\frac{z-s}{z}\right)^{5/3} ds$$

No calculation for downlink angle of arrival fluctuation has been made.

Bit Error Rate Measurements

The probability of error for a binary coded channel in the presence of log normal scintillation has been given by Fried [8] as

$$P_E = [2\pi\ (8\beta^4\sigma_\ell^{\ 2}\ X_T + \beta^2\ X_T)]^{-1/2}$$

$$x\ [\exp\ \{-\ \tfrac{1}{2}\ (4\beta^4\sigma_\ell^{\ 2}\ X_T + \beta^2\ X_T)\}\ ] \tag{24}$$

where β is the signal to noise ratio in the receiver and $\sigma_\ell^{\ 2}$ is the log amplitude variance of the scintillation. The parameter X_T is related to σ_ℓ and β by

$$\sigma_\ell^{\ 2} = -(\ell n\ X_T)/(4 + 8\beta^2\ X_T) \tag{25}$$

Equation 24 was derived under the assumption that the receiver noise is white gaussian noise. This assumption may not be justified for an optical receiver where the principle noise source is the Shott noise in the photodetector. A more precise treatment of detection in an optical communications system has been given by Hoversten [9]. For the purpose of estimating the dependence of P_E on the small changes in range the gaussian noise model should be adequate, however, so that Equation 24 may be used.

Inspection of Equation 24 reveals that the probability of error, P_E, depends only on the signal to noise ratio β and the log amplitude variance of the scintillation σ_ℓ^2. Provided that we may assume that the receiver noise remains constant then β is proportional to the received power which in turn varies as the square of the slant range. Hence,

$$\frac{\Delta\beta}{\beta} = 2\,\frac{\Delta S}{S} \tag{26}$$

For a 1000 foot change in slant range, a 5 mile radius path and altitudes of 42,000 and 63,000 feet this error amounts to 4.76% and 2.44%, respectively.

The changes in σ_ℓ^2 have been discussed in a preceeding section. It therefore remains only to demonstrate how these changes will effect P_E.

Equation 24 may be simplified by noting that for a small change in β or σ_ℓ^2 the first factor will be slowly varying compared to the exponential. We may therefore treat it as constant. Eliminating σ_ℓ we obtain

$$P_E = K \exp[-\frac{1}{2}\,(\frac{4\beta^4\,\ell n\,X_T \cdot X_T}{4 + 8\beta^2\,X_T} + \beta^2\,X_T)] \tag{27}$$

or

$$P_E = K \exp\,[-f(X_T,\beta)] \tag{28}$$

then

$$\frac{1}{P_E}\,\frac{\partial\,P_E}{\partial\,X_T} = -\,\frac{\partial\,f}{\partial\,X_T} \tag{29}$$

and

$$\frac{1}{P_E} \frac{\partial P_E}{\partial \beta} = - \frac{\partial f}{\partial \beta} \tag{30}$$

From Equation 25 it is seen that X_T may take on values from a very small positive number (deep scintillation) to +1 (no scintillation) while β can take on any positive value. For the case of fairly large signal to noise ratio and small scintillation $f(\beta,X_T)$ will reduce to

$$f(\beta,X_T) = \frac{1}{2} \beta^2 \left(X_T + \frac{1}{2} \ln X_T\right) \tag{31}$$

then

$$\frac{\partial f}{\partial X_T} = \frac{1}{2} \beta^2 \left(1 + \frac{1}{2X_T}\right) \approx \frac{3}{4} \beta^2 \tag{32}$$

$$\frac{\partial f}{\partial \beta} = \left(X_T + \frac{1}{2} \ln X_T\right) \approx \beta X_T \tag{33}$$

Then

$$\frac{\Delta P_E}{P_E} = - \frac{\partial P_E}{\partial X_T} \cdot \frac{\partial X_T}{\partial \sigma_\ell^2} \Delta\sigma_\ell^2 - \frac{\partial P_E}{\partial \beta} \Delta\beta \tag{34}$$

$$\frac{\Delta P_E}{P_E} = - \left(\frac{3}{4} \beta^2\right)\left(\frac{1}{8\beta^2 X_T}\right) \Delta\sigma_\ell^2 - \beta X_T \Delta\beta \tag{35}$$

$$\frac{\Delta P_E}{P_E} = - \frac{3}{32} \frac{1}{X_T} \Delta\sigma_\ell - \beta X_T \Delta\beta \tag{36}$$

Now for the assumed conditions, i.e., β large and X_T approximately equal to unity the first term is small so that

$$\frac{\Delta P_E}{P_E} = - \beta X_T \Delta\beta \tag{37}$$

From this analysis it is clear that even these with the simplifying assumptions the bit error rate may be a strong function of the signal to noise ratio, particularly for the case of large β. It may therefore be necessary to limit the experimental conditions to those producing large bit error rates.

A more exact analysis could be carried out by avoiding the simplifying assumptions which we have made and differentiating equation directly. However, due to the uncertainty as to the accuracy of the gaussian noise model it was not felt that such an analysis would be worthwhile.

Atmospheric Attenuation

The atmospheric transmission τ_A is given by [10]

$$\tau_A = \frac{\pi(\alpha\ S)^2\ \overline{I}}{P_T} \tag{38}$$

where S is the slant range to the aircraft; α the laser beam divergence angle, P_T the mean transmitted power and $\overline{I}$ the mean received power. In the preceeding section it was shown that for an altitude of 63,000 feet, I would change by about 2.44% per 1000 feet change in slant range. For attenuation measurements this variation is averaged so that small changes in the slant range have little effect on the observed value of τ_A provided that the average value of the slant range is accurately known. This information should be available from the GBAA. We therefore conclude that for changes in aircraft position of the order of a thousand feet will introduce errors of only a fraction of a percent into the measured value of τ_A. This is far less than the errors which may be expected in the measurement of $\overline{I}$ and P_T due to inaccuracies in the calibration of the detectors.

The atmospheric extinction constant K is related to τ_A by

$$K = -\frac{1}{M} \ln \tau_A \qquad (39)$$

Where M is the air mass. M is proportional to

$$\int_0^S e^{-h/h_o} \, ds \qquad (40)$$

Where S is the slant range and h is height above the ground. For the altitudes we are considering this integral is constant to within about 1/2%.

Conclusions

From the preceeding analysis, it is clear that the quantities to be measured on the HAAT experiment are relatively insensitive to small changes in either the altitude of the aircraft or its horizontal distance from the ground station. Of the two the latter is the more critical. In general, changes in aircraft position of 1000 feet will produce variations of only 1 or 2% in the measured statistical parameters. A typical data segment will probably be 1 or 2 minutes long. Experimental results indicate that the measured values of log amplitude variance taken a few minutes apart may differ by a considerable amount. It is therefore not unreasonable to expect the log amplitude variance to change by a few percent during the course of a measurement. If this is the case, then an additional variation of a few percent due to flight path inaccuracies will not be objectionable.

A possible exception is the bit error rate measurements. At very small bit error rates, the error rate becomes a very sensitive function of signal to noise ratio and therefore a sensitive function of received power. This, combined with the fact that a long time is required to measure a very small bit error rate, may make it difficult to compare the measured BER with theory.

Recommendations

It is recommended that the initial operational plan specify navigation tolerances during data acquisition of ± 500 feet in range from the ground station and ± 500 feet in altitude. These tolerances are to be held for one complete orbit around the ground station.

If it appears likely, either from discussion with Air Force personnel or from experience on early flights in the program, that these tolerances impose excessive restraints upon the operation of the aircraft, then they may be relaxed by as much as a factor of 2 or 3 without jeopardizing the validity of the experiment.

METEROLOGICAL DATA REQUIREMENTS

Introduction

The High Altitude Aircraft Test for Visible Laser Optical Communications requires that meterological data be collected prior to and during each test flight so that the optical measurements may be correlated with such gross atmospheric parameters as temperature, barometric pressure, relative humidity, and wind profile. In addition meteorological data will be useful in revealing unusual atmospheric conditions, such as a temperature inversion, which might lead to anomalous experimental results. A second, and equally important, requirement for meteorological data is to assist is scheduling the test at the most advantageous times from the point of view of favorable weather conditions. Also the test conductor must be provided with current and accurate forecast so that in the event of deteriorating weather conditions he will have the best possible information on which to base a decision to cancel or postpone the test flight.

Several sources of meteorological data are available. These include instrumentation which will be located at the Madkin Mountain ground terminal, the MSFC Atmospheric research station facilities located approximately three miles southwest of the ground terminal, the FAA Aircraft Advisory westher facilities located at the Huntsville - Decatur Airport five miles to the west, and several other weather stations on Redstone Arsenal operated for other purposes. In addition use will be made of the normal NOAA wide area weather information services. The MSFC Atmospheric Research Station will be the principal source of meteorological measurements and will assume primary responsibility for the collection and evaluation of weather information from all sources and for providing weather forecasts to the test conductor.

We have, at the direction of the contracting officers representative (COR), undertaken to review the meteorological support requirements for the High Altitude Aircraft Program. A preliminary statement of the meteorological data to be collected in connection with these test is given in the HAAT program plan [11]. We have carefully reviewed the meteorological measurements specified in that document to determine their value in analyzing the optical propagation data which will be obtained and to insure that no additional meterological data will be required. Several conferences have been held between the project director and MSFC Atmospheric Research Station personnel. On the basis of these conferences and our review, specific recommendations for meteorological data requirements have been formulated. We have also considered the question of what, if any, specific criteria can be established for the minimum weather conditions under which a flight test will be conducted.

Application to Measurements Program

Meteorological data will be used in the analysis of both the optical propagation experiments and the engineering experiments performed during the high sltitude aircraft test. Areas in which meteorological data will be employed include the following.

a) General Weather Conditions. For the optical propagation data to be meaningful it is necessary that the general weather conditions under which it was collected be carefully and quantitatively documented. The same is true, perhaps even to a greater degree, for the analysis of the communication and tracking systems performance. For this reason careful meteorological observations must be made throughout each flight. Special importance must be attached to the identification of any unusual conditions, such as temperature inversions or high, thin cloud cover, which might not be readily apparent to a casual observer.

b) Wind Profile. The frequency spectrum of the optical scintillation depends upon the component of wind velocity transverse to the optical path. Wind profile measurements will therefore be directly applicable to the analysis of the scintillation data. Fried [12] has developed expressions for the scintillation spectrum as a function of wind speed assuming that the wind speed is constant along the optical path. To our knowledge no analysis has been performed for the case of wind speed which varies along the optical path. Therefore additional theoretical work may be required in this area in order to properly interpret the results of the aircraft test.

c) Estimation of Structure Constant Profile. In order to adequately compare the experimental results to theory it would be desirable that the atmospheric structure constant, C_N^2 be measured as a function of altitude during each test. Methods of determining C_N^2 from the temperature structure constant have been proposed by Ochs [13,14]. It does not appear, however, that the instrumentation to make these measurements capable of being flown on a weather balloon will be available in time for use on this project. It will therefore be necessary to assume a standard profile for C_N^2 and to attempt to infer from conventional meteorological data the validity of this assumption. Information as such factors as temperature lapse rates will be useful in detecting conditions under which the C_N^2 profile may deviate from normal.

Test Scheduling

One of the most important applications of meteorological information will be it's use in scheduling the test flights at times when the weather conditions are likely to be the most favorable and in deciding when conditions warrent the postponement or cancellation of a test. The problem of scheduling will consist of three phases, viz. (1) Advanced scheduling of flight periods, (2) selection of specific flight times and (3) the decision to delay or abort a test in the event of deteriorating weather conditions.

We recommend that the following procedure and criteria be adopted for scheduling of flight test from a weather standpoint and for cancelling of a mission once it has begun.

A. Advanced Scheduling

The test will be carried out in sequencies of four flights. The operational periods for each sequence will be determined as far in advance as possible. In order to schedule the operational periods at times when most favorable weather conditions are likely to prevail it will be necessary to compile statistical data concerning the typical weather patterns at various times of the year in the Huntsville area. This data will include such factors as the average number of clear days per month, the typical monthly rainfall, etc. Based on statistics available for the past several years preferred operational periods will be established.

B. Selection of Specific Flight Times

One week before the beginning of each operational period tentative flight schedules will be established. The specific dates and times chosen will be based primarily upon a prediction of a low percent cloud cover and the absence of fog, haze or other conditions which might adversely effect the operation of the experimental system. The schedules must be considered tentative at this point since the reliability of one-week forecast is not very great.

Flight schedules will be reviewed at 5 days, 3 days, 48 hours and 24 hours before the beginning of each test. Rescheduling will be possible at each of these points if revised forecasts indicate an increased probability of fog, haze or excessive cloud cover.

C. Cancellation of Test

For the 24 hour period prior to the flight revised forecasts will be made every 6 hours and then hourly for the 6 hour period immediately preceeding the flight.

D. Criteria for Postponement of Test

It is recommended that the following criteria be used in scheduling and delaying a test flight.

1. Predicted cloud cover greater than 10 percent.

2. Any prediction of fog, haze, or cirrus clouds which might reduce atmospheric transmission below 70%.

Data Requirements

On the basis of our survey of the meteorological data required to support the High Altitude Aircraft Test and as the result of several conferences held with the MSFC meteorologist we recommend that the following meteorological measurements be made.

A. Madkin Mountain Ground Station

A meteorological shelter will be installed near the Ground Terminal on Madkin Mountain. Instrumentation will consist of a hydrothermograph to provide a continuous recording of relative humidity and temperature and a recording anamometer to measure wind speed and direction. Measurements at this site are required from 24 hours prior to the beginning of each test flight until 24 hours after the conclusion of the test.

B. At MSFC Atmospheric Station

1. Hourly observations from 6 hours prior to the beginning of each flight test until 1 hour prior to the beginning of the test, and then every 1/2 hour until the conclusion of the test. Observations will consist of:

a) Temperature

b) Barometric pressure

c) Relative Humidity

d) Wind Speed and Direction

e) Clouds, percent cover, type and approximate altitude

f) Surface visibility

2. Radiosonde Releases to provide temperature, relative humidity, wind speed and wind direction as a function of altitude from the surface

to 110,000 feet at 1000 foot intervals. Relative humidity measurement will not be made above 40,000 feet due to its low value above this level. It is expected that all of the sondes may not reach the specified altitude. This is not critical, however, since data above the operating altitude of the test aircraft is of only minor interest.

Two radiosonde releases are required for each flight test. The first will be made enough in advance of the arrival of the aircraft over station so that a complete profile will be available at the beginning of the test. The second release will be made near the mid-point of the test. In the event that the aircraft remains on station for the maximum time (4 hours) a third release near the end of the test would be very desirable.

C. Wide Area Weather Information

To aid in evaluating the local weather data and in predicting conditions at the time of each test wide area weather information is required. Meteorological FAX charts will therefore be supplied for surface, 500 mb., 700 mb. and 850 mb. every six hours of 48 hours preceeding and 24 hours following each flight.

ENGINEERING MEASUREMENTS PROGRAM

Introduction

The High Altitude Aircraft Test program plan contains, as Appendix B, a detailed measurements program for the scientific experiments which will be conducted. Engineering measurements are briefly outlined in Section III.C.5 (page 22) of the subject document. It was desired by the cognizant MSFC personnel that the engineering aspects of the HAAT program be documented in detail comparable to the scientific measurement program. We have, therefore, prepared at the request of the contracting officers representative this engineering measurements plan which describes the engineering and system analysis aspects of the Aircraft Test program.

Engineering Measurements

The measurements described in Sections III.C.1 through III.C.4 of the Measurements Program for the High Altitude Aircraft Test of Visible Laser Optical Communications are intended to yield fundamental information concerning the turbulence and transmission of the earth's atmosphere and their effects on wave propagation at optical frequencies. They will also provide critical data needed to design future optical communications systems for ground to satellite applications. In addition a number of engineering measurements will be made for the purpose of evaluating the performance of the tracking and communications systems and confirming the feasibility of the design concepts employed. These measurements will include:

a. Measurement of the return signal strength (joules/pulse) in the ground based acquisition aid (GBAA).

b. Determination of the maximum range for acquisition with the GBAA.

c. Measurement of the frequency of loss-of-track and time to reacquire.

d. Observation and video-recording of a real time television transmission.

e. Monitoring of certain "house keeping data" which will provide information on the operation and reliability of the various subsystems.

This data will be analyzed and evaluated in conjunction with other flight measurements, such as scintillation, and data from peripheral experiments as described below.

Engineering Analysis

1. Objectives

From an engineering viewpoint the high altitude aircraft test are intended to perform a number of functions. These include:

a. To demonstrate the feasibility of the technical approaches taken to the problems of acquiring and cooperatively tracking.

b. To demonstrate the feasibility of high data rate optical communication over vertical paths through the atmosphere.

c. To demonstrate the reliability of optical tracking and communication systems under actual operational conditions not too dissimilar to those which would be encountered in an earth to space link.

d. To provide engineering data which will be valuable in the design of future optical communications systems.

e. To identify the sources of error in the tracking and communications systems and to estimate their relative importance in terms of overall system operation.

In order to achieve these objectives a detailed evaluation of the operation of each subsystem should be performed. In the following section we have considered each subsystem and identified certain areas which we feel should be investigated and recommended measurements which should provide useful engineering data. In the following discussion it is assumed that the system is operating normally and within design specifications. Needless to say an important aspect of any engineering evaluation is the identification of those areas in which the system does not perform as expected or does not meet its design specifications. Since it may not always be possible to anticipate what these areas will be or what measurements should be made we have excluded measurements on malfunctioning systems from this discussion. Such measurements should more properly be considered trouble-shooting. We also exclude from consideration routine measurements which would fall into the category of acceptance-testing.

2. Ground Based Acquisition Aid (GBAA)

In the acquisition mode of operation the ground based acquisition aid (GBAA) depends upon the return of a single laser pulse in order to detect the incoming aircraft. This makes the system very sensitive to the effects of atmospheric scintillation since acquisition could be missed if the critical pulse occurred at an instant of deep fade. The designers of the GBAA (ITT Corp.) have attempted to minimize this possibility by dispersing the retro-reflectors on the aircraft over distances large compared to the correlation distances for atmospheric scintillation. In this way it becomes unlikely that all retro-reflectors will be in a region of fade at the same instant. This technique is in effect a form of aperture averaging for the returned signal. Considerable effort has been devoted to the analysis of the intensity of the returned pulses and the effect of dispersing the retro-reflector arrays [15].

It is important to the design of future acquisition and tracking systems that the effects of scintillation be experimentally determined and the effectiveness of dispersing the retro-reflectors be evaluated. This may be accomplished during the high altitude aircraft test by measuring the returned signal strength and comparing the observed data with the theoretical predictions. Quantities to be measured should include:

a. The mean intensity of the returned laser pulse.

b. The probability density function of the returned pulse amplitude.

In order to compare these measurements with the theoretical predictions both quantities should be measured simultaneously with scintillations experiments performed with the up and downlink communications systems.

A second engineering measurement on the GBAA will consist of determining the frequency of loss-of-track and the ability of the system to reacquire. It is expected that due to scintillation or system noise the GBAA will occasionally loose track of the aircraft. When this occurs the GBAA will automatically switch from the track-mode to a reqcquire mode and the presence of this condition will be indicated by a light on the GBAA control console. In order to measure the frequence of loss-of-track it will only be necessary to connect a counter to record the number of times the reacquire mode indicator is turned on. It might also be of interest to arrange a timer which would be started when the reacquire mode is entered and stopped when the track mode is entered. In this way the mean time required to reacquire the aircraft could be determined.

The expected frequency of loss-of-track will depend upon the detection probability for a pulse and thus may be computed in a manner similar to that used to determine the probability of acquisition. Comparison with the observed frequency with which track is lost will therefore provide an additional verification of the atmospheric model used in designing the GBAA.

3. Main Tracking System

Errors in the main optical tracking system are expected to arise from three sources; atmospheric scintillation, mechanical errors in the telescope mount and associated drive motors, and errors in the control electronics. Analysis of the tracking system should not only determine the overall tracking accuracy of the system but also should attempt to identify the contribution of each of these factors to the total system error.

Available data will consist of the telescope mount position encoders read-out, the signal to the fine pointing beam storers and the output signal from the tracking detector. The sum of these three signals will be the instantaneous bearing of the target aircraft. From this it will be necessary to remove the actual aircraft motion and the apparent pointing fluctuations due to atmospheric scintillation. Changes in the measured bearing due to actual aircraft motion can be assumed to be slow and smoothly changing so that the variance of the fluctuations about an instantaneous mean can be attributed entirely to system error or atmospheric effects. Simultaneous observation of scintillation will provide a measure of the integrated atmospheric turbulence along the optical path from which the angle of arrival fluctuations may be estimated.* After correcting the variance of the observed tracking fluctuations for actual target motion and atmospheric effects the remaining variation may be attributed to electrical or mechanical tracking errors. While this method is at best rough it is felt that it should yield a fair estimate of the tracking system performance.

4. Communications System

The principal engineering analysis which will be performed on the communications system will be measurements of bit error rates for the downlink P.C.M. system. These measurements have been described in detail in the scientific measurement program document so will not be discussed further here.

In addition to quantative bit error rate measurements a real time television picture will be transmitted to allow an evaluation of picture quality. By alternating between bit error rate measurement and

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*This estimate will not be exact since scintillation and apparent angle of arrival fluctuation depend upon the index of refraction structure constant multiplied by an appropriate lever function and integrated along the optical path. Since this lever function is not the same in both cases it will be necessary to make as assumption concerning the structure constant profile which may effect the result.

video transmission it will be possible to determine the bit error rate for each sample picture. Thus the subjective evaluation of picture quality amy be correlated with a measured bit error rate. Considerable research has been conducted to correlate bit error rates and picture qualities for R.F. television systems. However, because of the differences in the statistical nature of conventional communication channels and atmospheric channels it will be of interest to repeat these studies for an optical communications system.

The uplink communications channel will be used only to transmit operational commands to the airborne experiment package. Unless it should prove to be unreliable, which is not expected to be the case, it's operation will not be well suited to any type of quantitative analysis or evaluation.

Conclusions

In attempting to document an engineering measurements program one encounters certain difficulties not presented by a scientific measurement program. As a scientific experiment the high altitude aircraft project involves certain well defined aspects of optical propagation which one wishes to investigate. It is therefore possible to detail in advance exactly what data is required and what measurement should be made. From an engineering point of view the most interesting and important aspects of the experiment may well be those in which the experiment does not perform exactly as expected. If a system operates precisely as it was designed then there is no engineering problem of any importance left. This consideration makes it impossible to detail in advance all the engineering experiments which will probably be conducted in connection with the project. Secondly, unlike a scientific experiment where much qualitative data is collected, engineering experiments involve much more qualitative or subjective observation on the part of the personnel involved. That is to say an engineering experiment is often more of a learning experience for the engineer than a formal process of data taking and therefore much less subject to advance planning and documentation.

In the preceeding sections several areas have been identified in which it is felt an analysis of the operation of the High Altitude Aircraft Experiment hardware will lead to engineering data of value in the design of future optical communication systems. A number of measurements have been suggested to obtain this data. It is expected that as the MSFC operating personnel gain experience with the operation of the system many other engineering measurements will present themselves.

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